

Foreword

This fourth edition of the NASA Propagation Effects Handbook for Satellite Systems Design - A Summary of Propagation Impairments on 10 to 100 GHz Satellite Links With Techniques for System Design was prepared by Dr. Louis J. Ippolito of the Westinghouse Electric Corporation, under contract to The NASA Jet Propulsion Laboratory. Dr. Ippolito also coauthored earlier editions of the Handbook published in 1980, 1981, and 1983.

This Handbook was developed under NASA's Radio Science and Support Studies Program, which, with its predecessor programs, has been involved for two decades in the study of radiowave propagation over earth-space paths.

A companion NASA Handbook treats propagation effects at frequencies below 10 GHz (Propagation Effects on Satellite Systems at Frequencies Below 10 GHz - A Handbook for Satellite Systems Design, NASA Reference Publication 1108(02), 1987). Together, these two documents provide a comprehensive description of propagation factors affecting telecommunications systems involving earth-space links.

Earlier editions of the Handbook have enjoyed wide distribution and have served as a useful resource to the systems designer and planner in the evaluation of propagation impairments on satellite links. A NASA review panel, meeting in September, 1986, praised these handbooks and suggested that they be updated every four years, in synchronization with the CCIR cycle. It is our intention to adhere to that recommendation.

The NASA handbooks are evolving documents which strive to provide relevant information for both the propagation specialist and the satellite system designer/planner. Comments or recommendations for additional areas to be covered, or for improving the presentation of material, are always welcome.

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ABSTRACT

The NASA Propagation Effects Handbook for Satellite Systems Design provides a systematic compilation of the major propagation effects experienced on space-Earth paths in the 10 to 100 GHz frequency band region. The Handbook provides both a detailed description of the propagation phenomena and a summary of the impact of the effect on communications system design and performance.

The dominant effect - path attenuation due to rain - is dealt with in detail, in terms of both experimental data and the mathematical and analytical models devised to explain and predict the data. Other propagation problems covered include; rain and ice depolarization, gaseous attenuation, cloud and fog attenuation, scintillations, angle of arrival, bandwidth coherence, and sky noise.

The Handbook is arranged in two parts to facilitate efficient reference and application of the information. Chapters II through V comprise the descriptive part, which describes the propagation effects, prediction models, and available experimental data bases. Chapters VI and VII make up the system design portion of the Handbook. In Chapter VI design techniques and prediction methods available for evaluating propagation effects on space-Earth communications systems are presented. Chapter VII addresses the system design process and how the effects of propagation on system design and performance should be considered. Chapter VII also covers several mitigation techniques, such as site diversity and adaptive forward error correction (FEC), for overcoming adverse propagation impairments, and describes representative operational and planned K_u , K_a , and EHF satellite communications systems.

PREFACE

In the five years since the previous (third) edition of the NASA Propagation Effects Handbook for Satellite Systems Design was published, there have been many new developments in the analysis and evaluation of propagation effects on space communications links, as well as continuing growth of developmental and operational systems in the K_u , K_a , and EHF frequency bands, for civil, government, and international applications.

Major additions to this edition include:

- o updated versions of prediction models for gaseous attenuation, rain attenuation, and depolarization, including the latest CCIR models,
- o new measured data and propagation statistics,
- o a new fog attenuation prediction procedure,
- o new information on fade duration, low elevation angle effects, and ice depolarization,
- o up-to-date discussions on new technology topics relevant to above 10 GHz satellite communications, including SS/TDMA, beam switching/beam scanning systems, VSAT's, and adaptive mitigation techniques, and
- o descriptions of representative K_u , K_a , and EHF systems, including ACTS, INTELSAT VI, ITALSAT, and Olympus.

Extensive sample calculations and examples are included to highlight key analysis and prediction procedures. A new expanded index has been included to allow rapid access to topics of interest.

The contributions of Les Riddle and Katherine S. Han to Chapter VII of this edition, and the contributions of Roger Kaul, Ron Wallace, and George Kinal to earlier editions, are gratefully acknowledged. The contributions of Dr. Ernest K. Smith, University of Colorado, to Sections 6.8 and 6.9, and to the extensive draft reviews of this document, are also gratefully acknowledged.

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LIST OF COMMON SYMBOLS

Note: Throughout the Handbook the following symbols have been employed wherever practicable.

English

a	coefficient in specific attenuation (a_{Rb} - dB/km) relation
a	multiplicative coefficient in diversity gain relation (dB)
a	coefficient in XPD relation
$a_{1t}, a_{2t}, a_{3t}, a_{4t}$	coefficients in DD equations
A	total attenuation (dB)
A_{div}	total attenuation with diversity (dB)
b	coefficient in specific attenuation (a_{Rb} - dB/km) relation
b	coefficient in diversity gain relation
b	coefficient in XPD relation
$b_{1t}, b_{2t}, b_{3t}, b_{4t}, b_{5t}, b_{6t}$	coefficients in DD equations
B	beamwidth (degrees)
B_n	noise bandwidth (Hz)
c	speed of light in free space
C^2_n	Tatarski model coefficient
cm	centimeter
CNR	carrier to noise ratio
CP	circularly polarized

d'	separation between earth terminals
d_a	antenna diameter (m)
D	horizontal projection (basal) length of the path, raindrop diameter, number of hours of rain per year in RH model.
D'	parameter in DD model
$D\phi(p)$	mean square phase variation
DD	Dutton-Dougherty
e	partial pressure of water vapor (mb)
f	frequency (GHz)
f_f	fluctuation frequency (Hz)
F	probability modification factor of Dutton
g	gram
G_D	diversity gain (dB)
G_R	gain reduction (dB)
G/T	performance parameter of a ground station
h	hour
h_p	Planck's constant = 6.626×10^{-34} Watt sec ²
h_t	height of turbulence
H	height of OoC isotherm (km)
I	antenna isolation
$I(A)$	diversity advantage
I_c	coherent field component in Ishimaru model
I_i	incoherent field component in Ishimaru model
J-D	Joss-drizzle
J-T	Joss-thunderstorm
k	Boltzmann's constant = 1.38×10^{-23} joule/degree
km	kilometer

K_c	specific attenuation per unit water vapor density
K_ϕ	constant in phase variation model
l	effective path length (km)
l_c	effective path length of clouds
l_n	scale length of turbulent eddy (m)
l_o	parameter in Gaussian rain distribution scaling
ℓ	scale length of turbulent eddy (m)
L	path length (km)
L_e	effective path length (km)
L_e'	normalized effective path length (km)
L_o	parameter in turbulence model
L_t	path length through turbulence (km)
LP	Laws and Parsons, linearly polarized
m	meter
m_p	polarization mismatch factor
mm	millimeter
M	average annual rainfall (not including snow)
M'	link margin (dB)
M_d	mass of dry air (kg)
M'_o	no rain link margin (dB)
M_w	mass of water vapor (kg)
MP	Marshall-Palmer
N	refractivity
$\overline{\Delta N^2}$	mean square fluctuations in the refractivity N
N_d	raindrop size distribution function ($m^{-3}mm^{-1}$) or (cm^{-4})
N_o	constant in raindrop size distribution function ($m^{-3}mm^{-1}$) or (cm^{-4})

N_R	number of raindrops at rainrate R
p	pressure (N/m^2)
$P()$	conditional probability
P_{NOISE}	noise power (watts)
$P_t(R)$	percentage of year that t -minute rainfall rates R occur
q_{1t}, q_{2t}	parameters in RH rainfall model
r	path averaged rainrate (mm/h), axial ratio
r_e	mean earth radius = 6371 km
R	instantaneous rainrate in mm/h at one location
R_{1t}	parameter in Dutton-Dougherty Model
R_{ave}	path averaged rainrate (mm/h)
R_c	amount of water in a column (kg/m^2)
R_d	dry gas constant (joule/kgK)
R_w	wet gas constant (joules/kgK)
R_{st}	parameter in DD Model
R'_t	parameter in DD Model
RH	relative humidity, Rice-Holmberg
s	path length along the path
S^2	signal variance
t	time
T	temperature (K or $^{\circ}C$)
T	time period
$T_1, etc.$	instant in time period T
T_{2t}	parameter in DD Model
T_m	mean absorption temperature (K)
T_s	apparent sky temperature (K)

T_{st}	parameter in Dutton-Dougherty Model
$T_t(R)$	number of minutes the rainrate exceeds R for t-minute intervals
v	specific volume (m^3/kg)
v_d	detector voltage
v_c	visibility in fog (km)
XPD	crosspolarization discrimination
XPI	crosspolarization isolation
XPR	crosspolarization ratio

Greek

α	specific attenuation (dB/km), raindrop orientation angle
α_c	specific attenuation for clouds (dB/km)
β	ratio of rainfall during thunderstorms to total rainfall
β'	orientation of earth-terminal baseline
γ	multiplier in path averaged rain rate
δ	exponent in path averaged rain rate
θ	elevation angle, raindrop canting angle
λ	wavelength (m)
Λ	constant in raindrop size distribution function (cm^{-1})
ρ	distance along path (km)
ρ_ϕ	distance between phase variation points (m)
ρ_w	water vapor density (g/m^3)
σ^2_1	amplitude variance
σ^2_2	angle-of-arrival variance (deg^2)
σ^2_x	log-amplitude variance of signal amplitude
σ_ϕ	r.m.s. phase fluctuation

σ_e	r.m.s. phase scintillations
τ	polarization tilt angle
$\Delta\tau$	group delay (m)
\varnothing	azimuthal angle
$\Delta\varnothing$	group delay in radians

CHAPTER I INTRODUCTION

The satellite communications industry is currently in the process of a "frequency evolution", moving from the frequency bands that have been in use for decades, C-Band, X-band, SHF, etc., to the higher allocated bands above 10 GHz. These new bands, designated as K_u band (12-18 GHz), K_a band (27-40 GHz), and EHF (30-300 GHz), offer wider bandwidths, higher data rates, and smaller component sizes, as well as vastly improved anti-jam performance for secure communications applications.

The advantages of these bands can be offset very quickly however, by the realities of increased propagation problems as the frequency of operation is increased. Attenuation caused by rain in the path can be a serious problem, and careful design and adequate "rain margins" are essential for successful system performance.

There are other propagation mechanisms affecting Earth-space communications performance that are also of concern to the systems designer and planner. These include gaseous attenuation; cloud and fog attenuation; rain and ice depolarization; amplitude, phase, and angle-of-arrival scintillation; and sky noise.

The purpose of this Handbook is to provide, in one complete reference source, the latest information on critical propagation effects and how they impact communications system design and performance. NASA, who has supported a large part of the experimental work in radiowave propagation on space communications links, recognized the need for a reference handbook of this type,

and initiated a program in the late 1970's to develop and update a document which will meet this need. This present publication is the fourth edition of the NASA Handbook which focuses on propagation effects from 10 to 100 GHz. A companion handbook (Flock-1987) covers propagation effects on satellite systems at frequencies below 10 GHz.

1.1 OVERVIEW OF THIS BOOK

The NASA Propagation Effects Handbook for Satellite Systems Design provides a concise summary of the major propagation effects experienced on earth-space paths in the 10 to 100 GHz frequency range. The dominant effect--attenuation due to rain--is dealt with in some detail, in terms of both experimental data from measurements and the mathematical and conceptual models devised to explain and predict the data.

Other effects such as clear air attenuation and depolarization are also presented. The estimation of depolarization due to rain and ice has not been developed to the degree required for preparing good design estimates for satellite systems. Therefore, a comprehensive chapter on depolarization has been included that attempts to consolidate the work of several investigators in this area.

The Handbook has been arranged in two parts. Chapters II through V comprise the descriptive part. They deal in some detail with rain systems, rain and attenuation models, depolarization, and experimental data. This descriptive part of the Handbook is intended to provide background for system engineers and planners who want more detail than that presented in the later design chapters.

Chapters VI and VII make up the design part of the Handbook and may be used almost independently of the earlier chapters. In Chapter VI, the design techniques recommended for predicting propagation effects in earth-space communications systems are presented. Some selection has been made from alternative models in

order that only one design technique be utilized. This selection was made based on the ability of the technique to model the experimental results. The chapter includes step-by-step procedures for using the prediction models and numerous examples.

Chapter VII addresses the questions of where in the system design process the effects of propagation should be considered, and what precautions should be taken when applying the propagation results. The unadvised use of propagation results in the link margin can result in overdesign. This chapter bridges the gap between the propagation research data and the classical link budget analysis of earth-space communications system. This chapter presents generalized design procedures, and illustrates their use through extensive examples.

1.2 OVERVIEW OF PROPAGATION EFFECTS

The troposphere, and the hydrometeors (rain, snow, cloud droplets, etc.) it contains, can impair satellite communication links using the bands above 10 GHz in four ways:

Amplitude Reduction

The amplitude of the received signal is reduced from the "free-space" value through absorption and/or scattering by oxygen, water vapor, rain drops, and cloud and fog droplets. Of these, oxygen absorption in the 55-65 GHz band has the largest effect. Attenuation in this band is so great as to make Earth-space communication (at least from the surface) virtually impossible. At frequencies below the oxygen absorption band, water vapor becomes the most prominent attenuating gas. It causes a weak absorption peak (generally less than 1 dB on a vertical path, depending on humidity) in a band around 22 GHz. Both gases also cause appreciable attenuation above the oxygen band. Aside from oxygen absorption around 60 GHz, the greatest attenuation effect comes from rainfall. Because of its severity and unpredictability, rain attenuation rightly receives the most attention in the satellite system design

process for frequencies above 10 GHz. (Accordingly, it also receives the most attention in this Handbook.) Attenuation due to clouds is relatively minor compared to that of rain, but it is normally present for a much larger percentage of the time. It should be considered in systems operating above about 30 GHz, in locations where heavy rain is rare but cloudiness is common. Fog attenuation is not normally of concern in satellite systems because fog layers are relatively thin and do not usually occupy very much of the propagation path.

Thermal Noise Increase

Elementary physics tells us that anything that absorbs electromagnetic energy radiates it as well. The energy radiated by the tropospheric absorbing media (oxygen, water vapor, rain drops, etc.) is incoherent and broadband. It is received by the Earth station antenna along with the downlink signal, and appears at the receiver output as thermal noise - indistinguishable from the thermal noise generated in the receiver front end. The effect of the received noise energy is accounted for by adding a "sky noise" temperature to the Earth station receiver noise temperature. This sky noise temperature turns out to be related to the attenuation that the absorbing medium produces. Disregarding extraterrestrial sources such as the sun, sky noise temperature is zero when the attenuation is zero, and it asymptotically approaches the physical temperature of the medium as the attenuation becomes large. The effect of the thermal noise increase on system performance is to reduce the downlink carrier-to-noise ratio, which has exactly the same effect as an amplitude reduction on the downlink. However, because the thermal noise increase is additive, the magnitude of the effect depends greatly on the Earth station noise temperature in the absence of sky noise. For example, a 100°K sky noise contribution (corresponding to about 2 dB of rain attenuation) would produce a signal-to-noise ratio degradation of 3 dB if the system noise temperature was 100°K without rain, but the same sky noise

contribution would be negligible if the Earth station noise temperature started out at 1000°K.

Interference Increase

Systems that employ orthogonal polarizations to reuse the spectrum are subject to self-interference through crosstalk between the oppositely-polarized channels. The degree of self-interference is established by satellite and Earth station antenna performance, and by the depolarizing effects of rain drops and ice crystals in the path. Rain depolarization increases with rain rate and frequency and is well-correlated with rain attenuation. Depolarization from high-altitude ice clouds is normally associated with thunderstorms but can occur in the absence of rain attenuation. The effect of depolarization on the communication channel depends on the type of modulation used. For example, a given degree of depolarization will produce a greater increase in bit error rate on a digital link using QPSK than it would with BPSK. The effect of depolarization interference is fundamentally different from the amplitude reduction or noise increase propagation effects in that increasing the link power does not reduce the interference. This is because a power increase raises the level of the desired and the interfering signals simultaneously. Crosspolarization can be reduced, however, by employing a special adaptive rotation network on the antenna feed. Another type of interference that can be made worse by propagation effects is intersystem interference. Rain can cause scattering of electromagnetic energy out of the line-of-sight, resulting in increased leakage of uplink power into the receive beam of an adjacent satellite, or between terrestrial line-of-site systems and low-angle Earth station antennas.

Signal Modulation

Earth stations operating at low elevation angles are subject to scintillation caused by tropospheric turbulence. This consists of fast random fluctuations in the amplitude and phase of the signal. The effects of scintillations on the channel depend on the type of

modulation used and the receiver AGC performance. The power spectrum of the fluctuation falls off quickly with increasing frequency, so the effects should be expected to be primarily brief signal drop-outs or losses of synchronization, rather than any actual modulation of the information-carrying waveforms.

Propagation impairments are dependent on the following:

Operating Frequency. With the exception of signal attenuation by gaseous absorption lines, the severity of tropospheric impairments increases with frequency.

Antenna Elevation Angle and Polarization. The length of the part of the propagation path passing through the troposphere varies inversely with elevation angle. Accordingly, propagation losses, noise, and depolarization also increase with decreasing elevation angle. Rain attenuation is slightly polarization-sensitive. Depolarization is also polarization-sensitive, with circular polarization being the most susceptible.

Earth Station Altitude. Because less of the troposphere is included in paths from higher altitude sites, impairments are less.

Earth Station Noise Temperature. This determines the relative contribution of sky noise temperature to system noise temperature, and thus the effect of sky noise on the downlink signal-to-noise ratio.

Local Meteorology. The amount and nature of the rainfall in the vicinity of the Earth station are the primary factors in determining the frequency and extent of most propagation impairments. Rain-caused impairments depend on the rate of rain fall, so how the rain tends to fall (thunderstorms versus steady showers) is as important as the cumulative amount of rainfall. The type and extent of cloud cover, and local humidity characteristics, are other meteorological factors that determine the magnitude of propagation impairments.

Figure 1-1 shows the magnitude and variation of three significant tropospheric propagation effects: rain attenuation, sky noise due to rain, and rain depolarization. These are presented in

terms of their estimated exceedance statistics. The curves give the approximate percentage of an average year in which the magnitude of the effect exceeds the value given on the horizontal axis. The first plot gives rain attenuation for three frequencies: 14, 20 and 30 GHz. The second plot shows the signal-to-noise ratio degradation caused by rain attenuation and the accompanying sky noise increase. This is shown for 30 GHz, with three values of Earth station receiver noise temperature. The third plot is the cross-polarization isolation (XPI), assuming that the antenna's axial ratio is 0.4 dB. XPI is the ratio of the power received in one of the polarization channels to the "cross talk" power from the oppositely-polarized channel. The plot also gives, for two digital modulation schemes, the reduction in signal to noise density ratio that would have an effect on bit error rate equivalent to that of the cross-polarized interference.

The predictions shown in Figure 1-1 were derived using the procedures presented in this Handbook. The rain attenuation statistics were computed using the Global Model, following the steps outlined in Section 6.3.2. The thermal noise increase due to rain was computed using the formula given in Section 6.7.4. The depolarization curve was based on what is known in this Handbook as the "CCIR Approximation," which is presented in Sections 4.3.2 and 6.6.2. The correspondence between depolarization and equivalent degradation for BPSK and QPSK uses the results of Prabhu (1969).

This brief overview has been intended to introduce the system designer to the range of tropospheric effects to be expected on earth-space links operating at frequencies above 10 GHz so that he or she may more effectively use this Handbook. Other references relating to the general area of radiowave propagation effects include (Ippolito, 1981) (Ippolito, 1986), the IEEE Proceedings on Antennas and Propagation, and Radio Science. An excellent bibliography is also available (Dutton and Steele - 1982) for those seeking further general (or specific) literature.

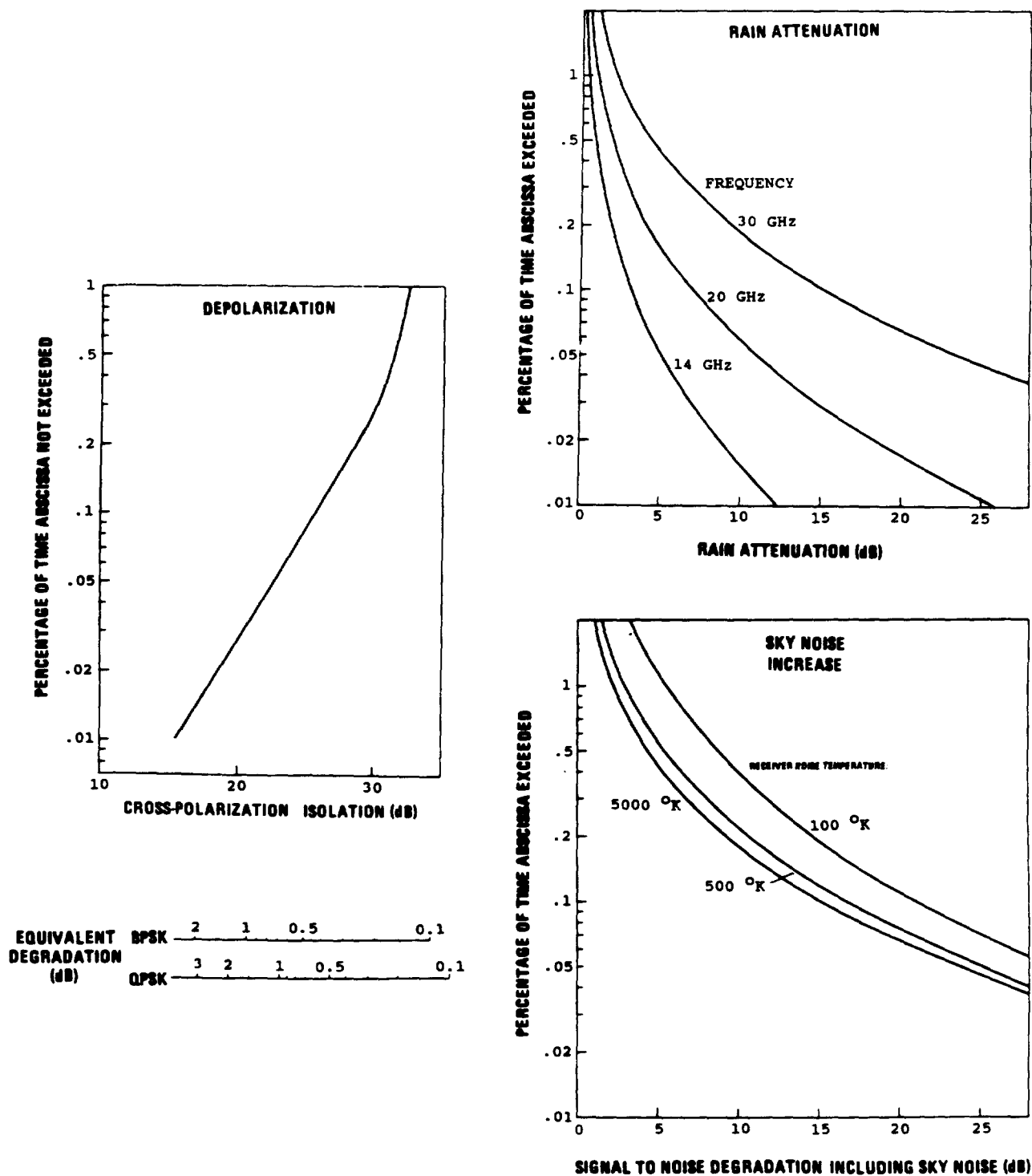


Figure 1-1. Predicted Propagation Impairments
for Washington, D.C., at sea level, Elevation Angle = 45.4°

1.3 References

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CHAPTER II CHARACTERISTICS OF RAIN AND RAIN SYSTEMS

2.1 INTRODUCTION

The attenuating and depolarizing effects of the troposphere, and the statistical nature of these effects, are chiefly determined by both the macroscopic and microscopic characteristics of rain systems. The macroscopic characteristics include items such as the size, distribution and movements of rain cells, the height of melting layers and the presence of ice crystals. The microscopic characteristics include the size distribution, density and oblateness of both rain drops and ice crystals. The combined effect of the characteristics on both scales leads to the cumulative distribution of attenuation and depolarization versus time, the duration of fades and depolarization periods, and the specific attenuation/depolarization versus frequency. In this chapter, we discuss how the characteristics are described and measured, and how the microscopic and macroscopic aspects are statistically related to each other. We also describe how one major propagation effect, specific attenuation, can be estimated. This information will serve as background for the rain and attenuation models of the next chapter.